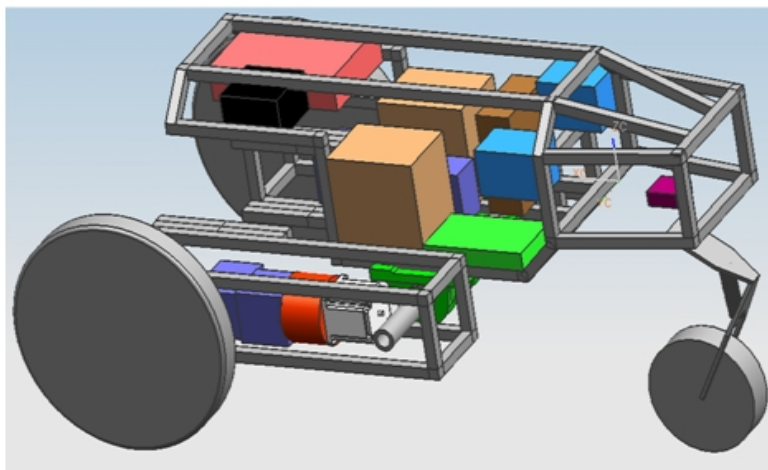


CHIMERA

Virginia Tech



Team members

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Required Faculty Advisor Statement

I certify that the engineering design of the vehicle described in this report, Chimera, has been significant, and that each team member has earned six semester hours of senior design credit for their work on this project.

A handwritten signature in black ink, appearing to be "Chris King".

1. Introduction

The Autonomous Vehicle Team of Virginia Tech is pleased to present Chimera, an innovative new vehicle designed specifically to compete in the Intelligent Ground Vehicle Competition (IGVC). Chimera gets its name from a mythical beast that had the features of a lion, serpent, and a goat all in one body. The combination of the three animals is symbolic of the design of our vehicle; it is powerful like a lion, has the ability to slither through obstacles like a serpent, and handles rough terrain like a goat. Chimera is a single-body, three wheeled vehicle with excellent mobility. The design features an electric power system, a custom-developed operator control unit with an emergency stop, an integrated power distribution board and refined software. Chimera exemplifies the 2006 team's effort to develop a new platform that combines the best safety, quality, reliability, and durability features from previous Virginia Tech vehicles. The team believes Chimera will continue to build upon Virginia Tech's success in IGVC.

2. Innovations

Virginia Tech's IGVC vehicles have been successful in the past, and the 2006 Autonomous Vehicle Team's goal is to continue the tradition of excellence in competition. While Chimera incorporates a number of innovative features found in previous Virginia Tech vehicles, it is distinctly different than its predecessors. Chimera has been designed and engineered to set a new standard for value and performance.

Chimera represents a new and exciting addition to the Virginia Tech autonomous vehicle fleet. Innovations to the vehicle include two low-profile camera masts that replace the taller mast found on previous vehicles, shown in Figure 2.1, a fully independent suspension, a streamlined weatherproof body enclosure, and a touch screen human interface device to control and monitor all functions of the vehicle. The addition of JAUS compliant software on the vehicle is another exciting innovation which will prove to be invaluable as future autonomous vehicle technology develops.

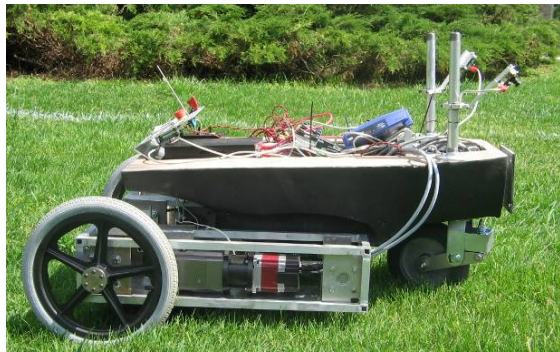


Figure 2.1: Chimera in development

Chimera was also created using an innovative design approach with a strong focus on value engineering. The base vehicle model has been designed to operate without a laser rangefinder, using the computer vision system for both line following and obstacle detection. This represents a reduction in vehicle manufacturing cost of nearly \$5,000. The laser rangefinder can be added for customers who desire this as an upgrade feature. We have also simplified the user interface and eliminated the need for an expensive and complex computer monitor. All user-available vehicle functions, including diagnostics, can be directly controlled or accessed from the LCD touch screen shown in Figure 2.2. This simplifies operation of the vehicle and reduces cost. We intend to run the value-engineered base model in competition, but we are also prepared to demonstrate the laser-rangefinder enhanced model for customers interested in our premium-performance package.



Figure 2.2: Chimera user interface

3. Design Process

The design process used by the Virginia Tech Autonomous Vehicle Team is known as DDP or the Definition, Design, and Produce approach to system development. The process is shown in Figure 3.1. It is a custom-developed iterative process that relies heavily on experience and careful examination customer needs and successful prior design

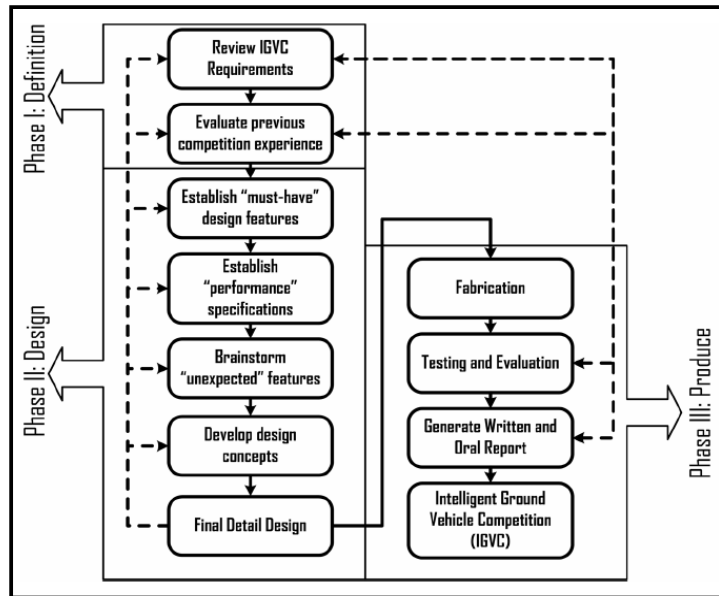


Figure 3.1: Layout of the iterative DDP design process

solutions. The process provided organization and a methodical approach throughout the design of the vehicle.

3.1. Definition Phase

The first stage of the DDP process is the *Definition* phase. During this phase the team reviewed the IGVC rules and previous vehicles, identifying the customer needs and user requirements for the new vehicle design. The team identified the following customers: the IGVC judges, the design team, project advisors, sponsors, other research and educational project teams that may use the vehicle, and Virginia Tech. Key customer needs identified were the ability to: (1) meet all the 14th annual IGVC rules, (2) provide performance and value to the customer, (3) build a reliable test platform with a small turning radius, (4) provide extended run time, (4) develop a simple, compact system that is easy to transport and operate.

3.2. Design Phase

In the *Design* phase, the team followed the KANO design method described in *Attractive Quality and Must-Be Quality Method* (Kano, Seraku, Takahashi and Tsuji, ASQC Quality Press, 1996). Figure 3.2 shows the methodology of the KANO process. This design method consists of three main components; “must haves”, “performance features” and “delighters”.

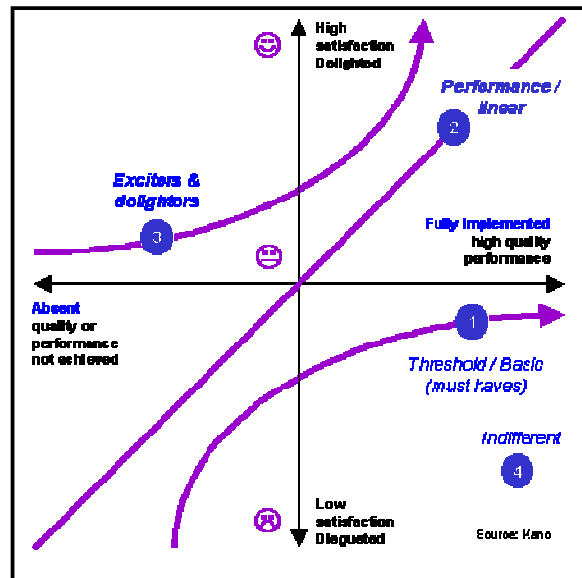


Figure 3.2: KANO design methodology

The KANO model predicts customers’ satisfaction for particular design features. The team’s goal is to design a vehicle that will perform well, exceed competition requirements, and contain delighters that will increase customer satisfaction. Delighters are unexpected features that are not widely adopted by the competition, but that enhance the customer’s positive feelings about performance, value and quality. The KANO method was the motivation for the innovations listed in Section 2. Safety, mobility, autonomy, 5 mph max speed, E-Stop, and payload space are examples of a few “must have” features listed by the team.

3.3. Design Variations and Challenges

The team’s first design began with a brainstorming session where each member presented ideas for the vehicle. The team voted on specific ideas and features and developed

an initial vehicle design concept. Some of features voted on by the team included the number of bodies, number of wheels, and type of steering. As shown in Figure 3.3, several of the initial design features included one body, four wheels with skid steering, and two cameras. As the design process progressed, the team conducted design review meetings with members from previous years, graduate students, and the team advisor. The constructive criticism and recommendations received during the meeting helped the team reevaluate their design. Figure 3.4 shows the chosen design that includes full suspension on the two rear wheels and the caster wheel, differential steering, and drive boxes that are separate of the main body. The final design, shown in Figure 3.5, was created after further refinement of the initial and intermediate designs.

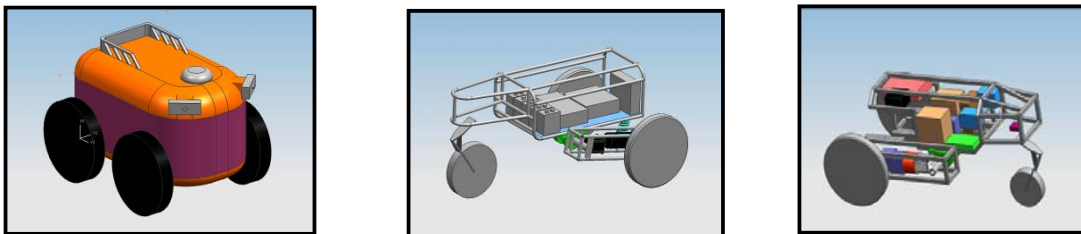


Figure 3.3: Initial vehicle design **Figure 3.4:** Intermediate vehicle design **Figure 3.5:** Final vehicle design

3.4. Production Phase

The *Production* phase of the design process consists of the manufacturing, testing, and evaluation of the vehicle. Using design specifications and CAD models, the team built the vehicle frame and placed components in efficient locations. The vehicle and all subsystems were fabricated completely by the team. Extensive testing and evaluation of the vehicle are also important steps in the *Production* phase. The vehicle's performance was tested and refined during extensive field trials. The final step of the *Production* phase is attending the 14th annual IGVC.

3.5. Team Organization

The team divided into three sub-teams to focus on specific areas of the design. The team structure, including software, electrical, and frame sub-teams, is shown in Figure 3.6. Although members of the team were assigned to a particular sub-team, each person had the opportunity to assist in tasks outside their designated areas. A total of 4224 hours were spent in the design, development, and testing of Chimera.

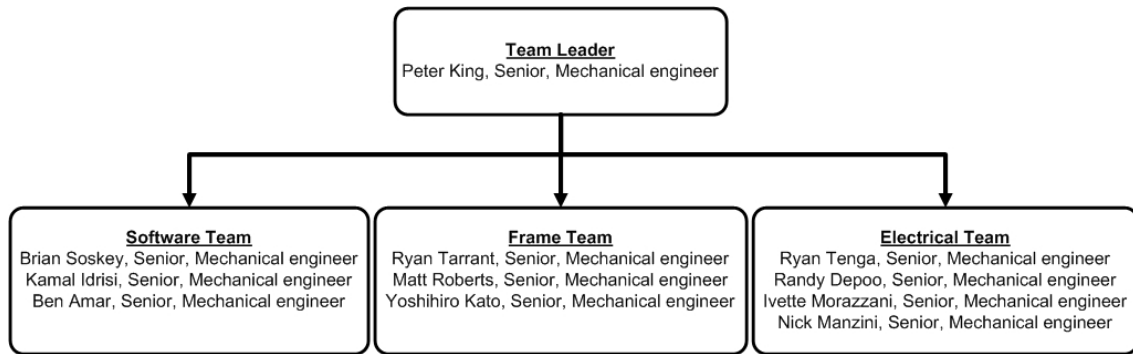


Figure 3.6: Chimera team structure

4. Base Vehicle

Chimera is a three-wheeled, differentially steered vehicle. The frame was fabricated from ¾” square 6063 aluminum tubing with 1/8” thick walls. The 6063 aluminum reduces magnetic interference with the digital compass and signal lines, as well as reducing the overall weight of the vehicle. Chimera is protected by a fiber-glass outer shell, split into an



Figure 4.1: Inverted Fiberglass body

upper and lower section. The lower section of the vehicle is shown inverted in Figure 4.1. Chimera features a fully independent suspension with shocks mounted on each motor box and a custom designed front caster wheel with suspension. The suspension was included to help minimize shock to sensitive components.

Chimera’s total weight of 200 lbs is distributed in a ratio of 40/60 between the front and rear wheels, respectively, resulting in greater traction on the rear drive wheels. Care was taken to mount heavy components low in the vehicle to lower the center of gravity. Chimera is 31 inches wide, 24 inches tall, and 50 inches long. This size allows it to drive through a standard 32 inch doorway, which is an important consideration for many prospective customers.

4.1. Drive Train

The vehicle drive train is entirely contained in two independent motor boxes that articulate with respect to the vehicle body. This configuration allows the drive wheels to be mounted on a simple swing-arm suspension. It also facilitates drive train maintenance or replacement of the entire drive mechanism. Each drive box is attached to the vehicle via a shaft connected to the main body by Timken eccentric locking bearings. This connection

allows for the drive box suspension systems to articulate independently with respect to the main body. Figure 4.2 shows the drive train and drive box design.

Each drive box on Chimera contains a QuickSilver I-Grade 34HC-1 brushless DC servomotor. The motors have a maximum power of 0.76 horsepower at 2.03 ft-lb of torque with a continuous stall torque of 6.78 ft-lb. The motors are controlled by QuickSilver I-Grade N3

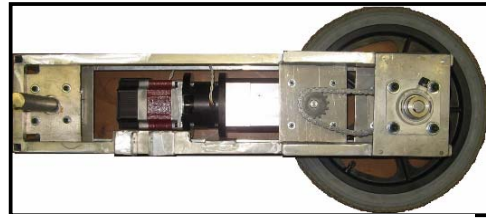


Figure 4.2: Individual motor box and drivetrain

SilverNugget controllers. Directly coupled to each motor is a 10:1 reduction NEMA 34 right angle gearhead. Figure 4.2 shows the drive train and drive box design. The gearhead is connected to a custom driveshaft and wheel hub via chain and sprocket, reducing stress on the gearhead. This driveshaft is supported by two Timken polycarbonate eccentric locking bearings and connected to the wheel outside of the drive train box.

4.2. Safety

There are several key features of Chimera that contribute to the safety of the vehicle. Sealed lead acid batteries are used to reduce the risk of hazardous material spillage during operation or transport. In addition, the user interface is located at the rear of the vehicle close to the emergency stop button. Warning lights blink when the vehicle is in operation or changing modes of operation.

5. Electrical System

The electrical system in Chimera is extremely compact, minimizing the number and length of wires used on the vehicles. The overall electrical system is best described by breaking it up into two main sections; power distribution and sensor/component communication.

5.1. Power Distribution

The power distribution for the vehicle is accomplished through the two custom designed circuit boards shown in Figure 5.1. These boards are stacked together in the vehicle during operation. The first board is responsible for power input and regulation. Two 12 Volt sealed lead acid batteries connected in series supply the board with 24 Volts at two separate inputs. The first input sends the 24 Volts through three DC to DC Voltage regulators; one 24 Volt regulator and two 12 Volt regulators which supply power to the second board. The second input is used to send an unregulated 24 Volts to the motors and the brakes. This

power can be interrupted by a remote emergency stop or a hard wired button, triggering the brakes and immediately stopping the vehicle. The vehicle uses one main power switch to control the entire electrical system.



Figure 5.1: Power distribution boards: Input & Regulation (left), Distribution & Monitoring (right)

The second board receives regulated 12 and 24 Volts and is responsible for power distribution and monitoring. The regulated 24 Volts is distributed to the optional Laser Range Finder (LRF) and to an auxiliary connector. The regulated 12 Volts is sent to the ITX Computer, compass, GPS, router, JAUS light, and to an auxiliary 12 Volt connector. Each of these connectors has an individual fuse to avoid damage from a power surge. The board incorporates a microcontroller, allowing sensors to be turned on and off electronically via relays. This microcontroller is also capable of monitoring the voltage that each sensor is receiving, as well as the board temperature. All this information can be monitored by the computer through an RS-232 connection. The entire power distribution system is outlined in Figure 5.2.

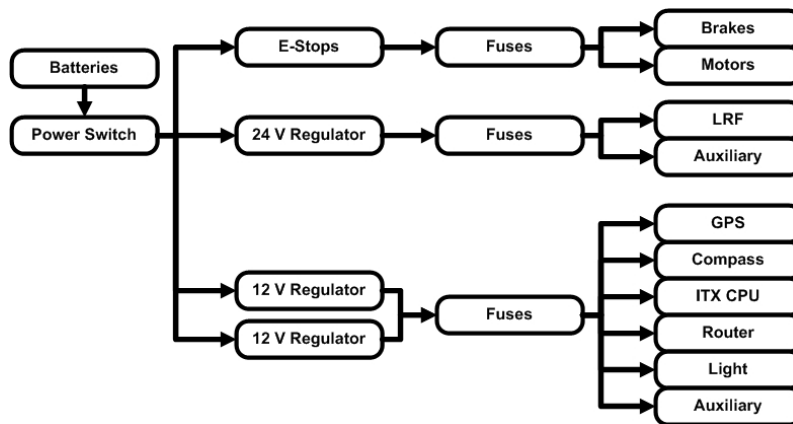







Figure 5.2: Chimera's power distribution system

5.2. Sensors and Computing

Four sensors, including the optional laser rangefinder, are implemented in the design of Chimera. These are described in Table 5-1 along with the main ITX board computer that for interpreting sensor inputs and making navigation decisions.

Table 5-1: Summary of sensors used on Chimera

Sensor	Description	Picture
Unibrain Fire-I board Camera	Chimera utilizes two OEM Unibrain Fire-i board Firewire cameras with a native 640 by 480 pixel resolution and 15 frames per second (fps) update rate. The lenses are 2.1 millimeter fixed focal lenses that provide an 80.95° horizontal view angle. The cameras are used for both detecting lines as well as obstacles.	
SICK LMS-221 Laser Rangefinder	The SICK LMS-221 laser rangefinder (LRF) scans in a horizontal plane and returns the distance to obstacles within 80 meters at a resolution of 1°. The LRF is an upgradeable option on Chimera, as Chimera can also use cameras to detect obstacles.	
Novatel ProPak-LB DGPS	Chimera uses a Novatel ProPak-LB Differential Global Positioning System (DGPS) to determine its position. Using the OmniStar HP correction service improves accuracy such that 99% of all position readings within 15cm from the true position.	
PNI TCM2-20 digital compass	The PNI TCM2-20 digital compass senses vehicle heading relative to magnetic North. It is a tilt compensated instrument and is used in the Navigation challenge to determine vehicle heading. In addition, it is accurate from 0.5° to 1° depending on tilt.	
ITX board	The ITX board is a compact and inexpensive alternative to a laptop computer. The board is equipped with a Pentium M 735 processor and 1 GB RAM. In addition, the ITX board is protected by a steel ventilated case and is located in the rear of the vehicle.	

5.3. Sensor and Component Communication

An important goal of the electrical team was to minimize the number of wires routed through the vehicle. The digital cameras are connected directly to the ITX via Firewire, while the motors, compass, GPS, and LRF are equipped with serial to USB converters. USB cables from each sensor are then connected to a USB hub at the front of the vehicle. By using the USB hub, only a single USB cable is required to connect the sensor suite to the ITX board computer. The serial to USB converters allow for the sensors and motors to be disconnected individually as needed for quick removal and repair. A wireless router is connected to the ITX through a CAT-5 Ethernet cable, allowing the use of remote desktop to monitor and program the software on the vehicle. A diagram of the communication setup is illustrated in Figure 5.3.

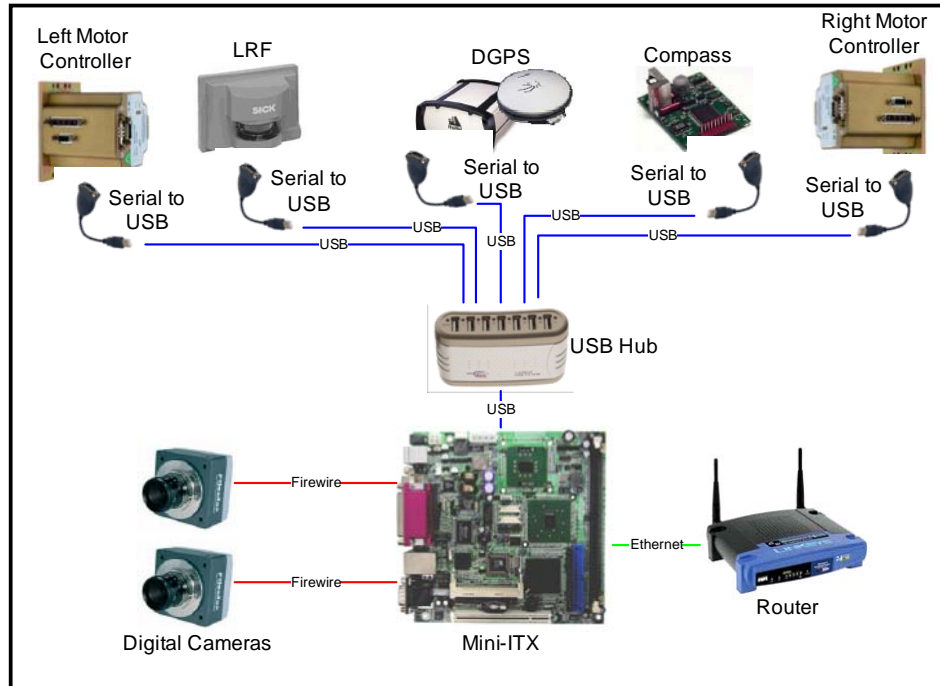


Figure 5.3: Sensor and component communication diagram

6. Software

The software design of Chimera is an evolution of previous competition software with a focus on value engineering. Eliminating the laser range finder and detecting obstacles solely with the computer vision system proved to be challenging, but the result are also immensely rewarding. The two-camera arrangement used to provide an expanded field of view also allowed the team to lower the camera masts, eliminating the typically large masts found on most other vehicles. The result is a much less expensive, more compact and lower-profile vehicle with all the functional capabilities found in our earlier designs.

6.1. Autonomous Challenge

The Autonomous Challenge software uses two Unibrain firewire cameras to navigate through the course. The steps to complete this task are shown in Figure 6.1. First, the cameras acquire a color image of the course in front of the vehicle. These

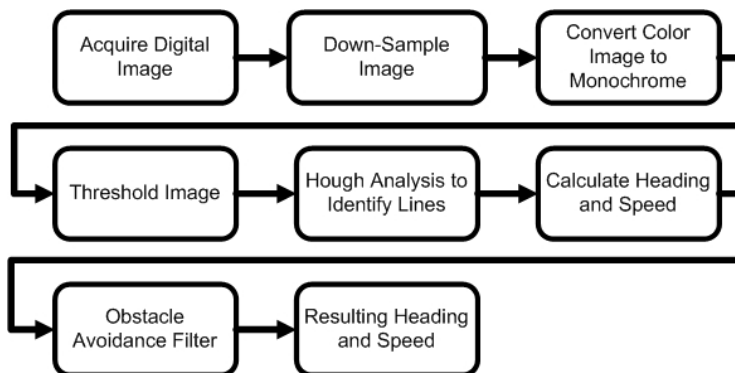


Figure 6.1: Autonomous challenge software algorithm

images are resized from 640x480 pixels to 160x120 to reduce processing time. After the image has been resized, it is converted to a monochrome image and thresholded to separate the white lines from the rest of the image. A Hough transform is then performed on the threshold image to identify the most dominant line in the image. Line characteristics, such as orientation and score, are then passed to a decision tree where heading and speed are determined.

Once heading and speed are determined, this information is processed through an obstacle avoidance filter. New to Chimera is the “virtual LRF” where the camera images are analyzed to find obstacles. This obstacle information is formatted to match the output of a LRF, allowing the software to use a LRF or the “virtual LRF” with no modification. An in-depth description of the obstacle detection process is presented in the next section. The final step is to combine the heading and speed with the information about any obstacles in front of the vehicle. A heading is selected that is closest to the one suggested by the line following algorithm while avoiding the obstacles.

6.2. Obstacle Detection and Avoidance

The Autonomous Challenge and Navigation Challenge both depend on the detection and avoidance of obstacles. Chimera uses a vision-based obstacle detector, eliminating the weight and cost associated with the traditional laser rangefinder. Through processing and manipulation, images may be used to simulate the functionality of a laser rangefinder. Figure 6.2 shows the steps used to detect obstacles in an image.

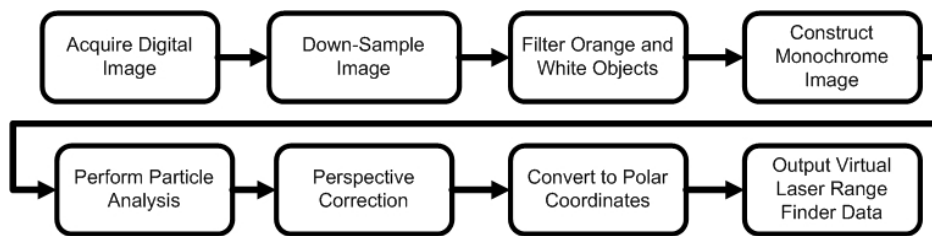


Figure 6.2: Process used to detect obstacles from an image

The raw images from the cameras are first down-sampled to reduce processing time. Each image is then filtered to isolate orange and white objects; from this, a monochrome image is constructed. Using geometric criteria such as minimum area and aspect ratio, a particle analysis process identifies objects within each monochrome image that meet the empirically determined criteria characteristic of obstacles. Next, a perspective correction algorithm uses the position of the objects within each image to calculate where they are in

relation to the vehicle. The resulting set of coordinates mimics the output of a laser range finder and the results are output as an array of polar coordinates spaced 1° apart. The left and right images are processed separately, and the resulting polar arrays are combined and sent to the obstacle avoidance software. Using this information, a vehicle path is selected from a set of arc-shaped paths. A path will be chosen that takes the vehicle closest to the desired heading without hitting an obstacle.

6.3. Navigation and True North Challenge

The Navigation Challenge algorithm relies on path generation and velocity optimization to ensure that the vehicle follows an optimized path based on its current location, its dynamic properties, and the location of the waypoint. Figure 6.3 shows the steps to calculate left and right wheel velocities

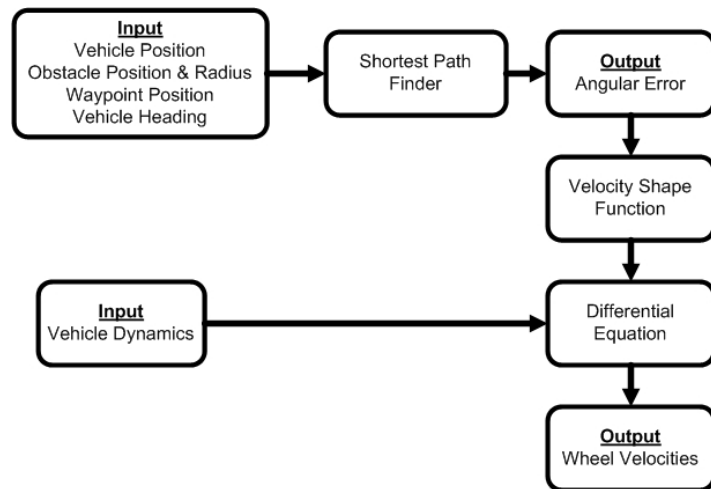


Figure 6.3: Path generation algorithm for the navigation challenge

necessary to move the vehicle. The GPS, digital compass, and cameras feed information to the shortest path finder. The result of the shortest path finder produces an array describing the shortest path between the vehicle and the waypoint while avoiding obstacles. If there is no obstacle, the shortest path is a straight line, and a constant heading. If obstacles are in the way, the points are used to calculate desired headings for the vehicle to follow. Figure 6.4 provides a visual representation of the shortest path finder.

Once the shortest path is generated, the angular error (the difference in the desired and actual headings) is calculated. Next, a velocity shape function, shown in Figure 6.4, determines a safe velocity based on this calculated angular error. For example, large angular errors limit the vehicle's speed to a minimum value, while a small angular error increases the vehicle's speed to the 5 MPH limit. Having determined the forward velocity, the turning radius is calculated from the velocity and known acceleration limits.

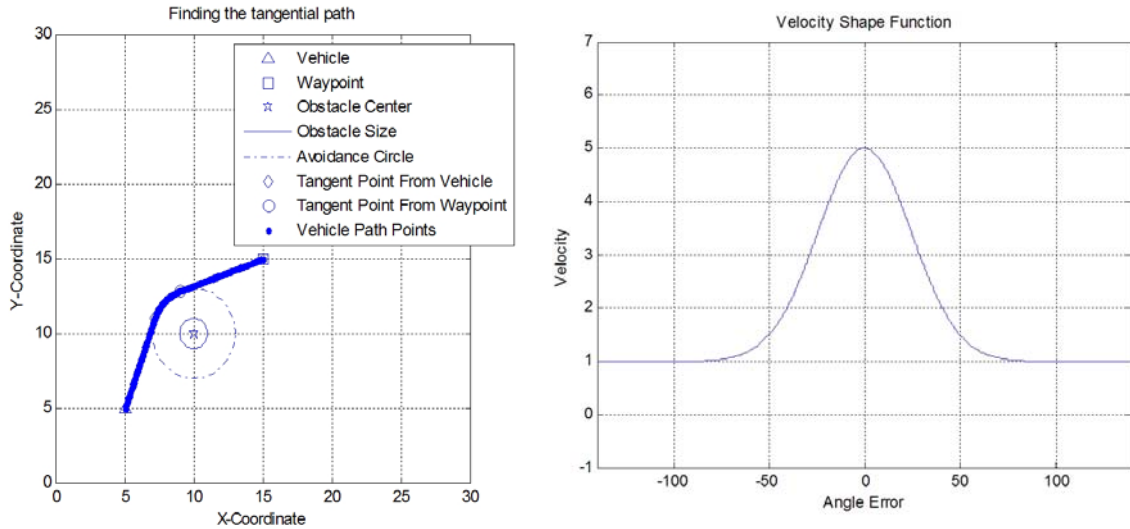


Figure 6.4: Shortest path example (left) and velocity shape function (right)

6.4. JAUS Challenge

Virginia Tech has been involved with JAUS for over a year. The team first learned JAUS by using LabVIEW software libraries developed by students at Virginia Tech. The team was instructed on the theory behind JAUS and the implementation of the developed software.

To address, the requirements of competition the team has included a “JAUS Competition” menu on the user interface panel. Once selected, the vehicle is activated and set to wait for JAUS commands. Exiting the JAUS Competition mode is simply a matter of navigating back to the main menu on the control panel. At this point JAUS commands will no longer be accepted.

The JAUS reader created for Chimera addresses the competition directly and only handles the applicable header information. Once the message is received, the header is parsed to extract the destination JAUS ID, the command code, and, if necessary, the message body. If the JAUS ID matches the vehicle’s JAUS ID, then the vehicle will act on the command code, reading the message body if it is to activate/deactivate the JAUS horn or other discreet device.

7. Predicted Performance

Several factors were including in determining the vehicle’s predicted performance, including speed, reaction time, runtime, battery life, ramp climbing ability, obstacle detection distance, traps and potholes, and accuracy of navigation waypoints. The predicted performance was compared to the actual performance during many trial runs.

7.1. Speed

QuickSilver brushless DC motors with a 10:1 gear reduction have a maximum no load rotational speed of 3000 RPM. When using 14” tires, the vehicle can obtain a maximum no load speed of 14.2 mph. In testing, the vehicle was able to achieve speeds of more than six MPH on a level surface. Although, the vehicle speed is limited to a maximum of 5 MPH to comply with competition rules.

7.2. Reaction Time

The reaction time of the vehicle is based on the computational time for a single cycle of software repetition during the autonomous challenge. A summary of the results is shown in Table 7-1. The table shows the maximum time for each process. With a total maximum cycle time of 120 ms, the software will update at a minimum rate of approximately 9 Hz. This rate will increase if there are few obstacles near the vehicle or under other simplified cases of navigation. Reaction times for the navigation challenge are approximately 15 Hz. Reduced complexity in the processes of waypoint navigation is the main factor in the increased reaction speed.

Table 7-1: Autonomous Challenge Software Cycle Times

Process	Time (ms)
Vision based Line Analysis	36
Vision based Obstacle Detection	46
Obstacle Avoidance	33
Total	120

7.3. Run Time & Battery Life

Table 7-2 lists the vehicle’s components and power requirements. These estimates are determined from the maximum power consumption specification or empirical results. All power is supplied by two sealed lead acid batteries in series with 26 amp hour capacity. The vehicle run time is determined by the battery life. From the data listed Chimera has an estimated runtime of over 3 hours.

Table 7-2: Sensor & Component Power Requirements

Sensor/Component	Voltage (Volts)	Current (Amps)	Power (Watts)
Compass	12	0.02	0.24
GPS	12	0.53	6.36
ITX	12	5	60
Motors	24	5	120
Brakes	24	0.42	10.08
Total Watts			196.68

7.4. Ramp Climbing Ability

During competition the vehicle is expected to clear a 15% grade (8.5 degrees) ramp. However, for future applications it is valuable for the vehicle to climb even steeper ramps. During testing it was possible to drive the vehicle up an incline of 26% grade (15 degrees).

7.5. Obstacle Detection Distance

During the autonomous and navigation challenges, obstacles will be detected using two Firewire cameras. Each camera has a usable range of 10 ft. Figure 7.1 shows the overlap of the views from each camera and the “blank spots.” Chimera also has the option for a laser range finder. The scanning laser rangefinder has a range of 80 meters (262.5 feet), but the current navigation software ignores obstacles that are further than three meters (9.84 feet) away from the front of the vehicle. This range is sufficient to allow consideration of multiple obstacles and obstacle trends prior to determining the best forward path of the vehicle.

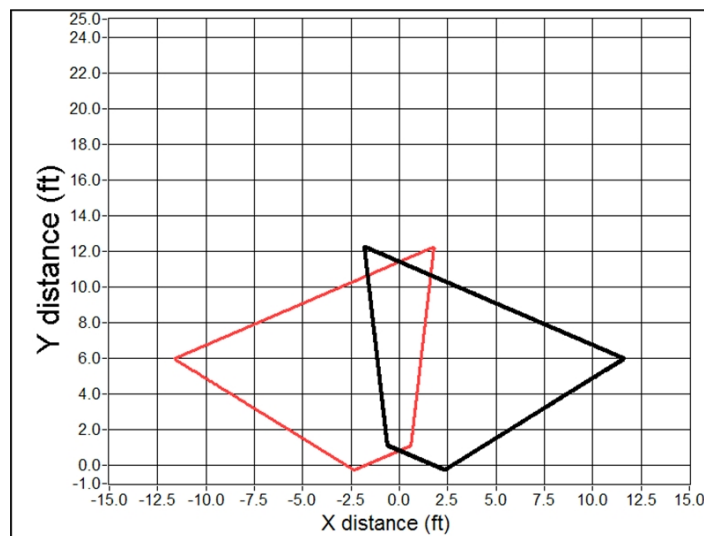


Figure 7.1: Field of view of each camera

7.6. Dead Ends, Traps, and Potholes

The best way to prevent dead ends and traps is by efficient path planning in the software. However, in the event of a dead end or a trap situation, the software is designed to perform a zero-radius turn until the vehicle is extricated. This software feature, along with the single body zero-turn-radius design of Chimera allows it to turn away from obstacles and find a clear path. Large white regions, designating a pothole, that are encountered during the Autonomous challenge are detected by the two Firewire cameras and are treated as obstacles.

7.7. Accuracy of Arrival at Navigation Waypoints

Testing showed Chimera can consistently navigate to GPS waypoints to within less than one meter, given good quality GPS signals and a reliable differential correction. Specifically, the Novatel GPS unit provides for sub decimeter accuracy when coupled with OmniStar HP correction service.

7.8. Accuracy of Headway and Lateral Deviation Maintenance

The digital compass displays a $\pm 0.5^\circ$ to $\pm 1^\circ$ heading accuracy depending on the amount of tilt experienced by the unit. The GPS unit is able track the global position of Chimera with sub-meter accuracy and continually augments the navigation algorithm to assure the lateral deviation is minimized.

8. Vehicle Cost

Throughout the design and fabrication of Chimera, the team was able to attain donations and discounts from a number of companies and vendors. Thanks to their support the development cost of Chimera was greatly minimized. In addition, we were able to share some equipment with other research teams at Virginia Tech and previous autonomous vehicles that are not competing in the 14th Annual IGVC. Table 8-1 provides a cost summary for Chimera. Upgrading to the full laser rangefinder equipped version adds more than \$5,000 to the manufacturing cost of the system.

Table 8-1: Cost breakdown of Chimera (base model)

Part Description	Retail Cost	Cost to Team
Digital Compass	\$700.00	\$0.00
(x2) Cameras	\$269.00	\$219.00
GPS	\$8,000.00	\$0.00
(x2) Motors	\$1,290.00	\$1,075.00
(x2) Nuggets	\$1,200.00	\$999.72
(x2) Gearheads	\$2,356.00	\$2,142.00
(x2) Brakes	\$548.00	\$498.00
Caster Wheel	\$56.46	\$56.46
(x2) Skyway wheels	\$53.00	\$53.00
6061 Aluminum	\$82.00	\$82.00
Fiberglass	\$250.00	\$250.00
Shocks & Bearings	\$220.00	\$220.00
(x2) Batteries	\$113.00	\$113.00
Battery Charger	\$159.00	\$159.00
Router	\$70.00	\$70.00
Electrical System Components	\$432.00	\$432.00
Computer System	\$735.00	\$735.00
Total	\$16,533.46	\$7,104.18

9. Conclusion

Chimera is an autonomous vehicle designed, fabricated, and tested by a team of undergraduate students at Virginia Tech. Its innovative and original design separates Chimera from previous Virginia Tech vehicles. The durable construction, reliable electronics, and refined software contribute to Chimera's overall performance. The use of removable motor boxes for the drive train and a simple and integrated printed circuit board electronics system allow for easy troubleshooting and future upgrades. Furthermore, the development of the computer-vision-based "virtual laser rangefinder" and the simple LCD touchscreen exemplify our focus on value engineering. By following a rigorous design process, the team was able to design and manufacture a fully autonomous vehicle that we expect to perform at a high level in all three events at the 14th annual IGVC.